VIBRATION ANALYSIS AND DESIGN METHODOLOGY FOR SINGLE-IMPACT AND DOUBLE-IMPACT TRIBOELECTRIC GENERATORS

D. Bhatia, D. Choi

Nanostructures and Nanomaterials Laboratory, Department of Mechanical Engineering, Kyung Hee University, South Korea

divijbhatia@khu.ac.kr, dchoi@khu.ac.kr

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Abstract

Remote low power devices that will constitute the internet of things can be powered by scavenging energy from environmental mechanical vibrations. Triboelectric generators (TEG) are devices that can be used to convert vibration motion into electrical energy. In this paper we explore how freely vibrating TEGs excited indirectly by external forces may be designed. The design of TEGs depends on several variables and application specifications. First the system is modeled and the related parametric variables are studied. A design algorithm is proposed to achieve resonance condition. Based on the algorithm single-impact TEG and double-impact TEG devices were fabricated and their vibration behavior measured. The double-impact TEG showed four times improvement in voltage output and two times improvement in operation frequency bandwidth. Finally, the proposed system model was simulated using MATLAB for the two TEG designs. It was shown that the simulation supports the experimental results.

1 Introduction

Vibration energy is prevalent in our daily lives within the environment and in several operating machines. We lose most of this mechanical form of energy that instead can be scavenged and utilized to power our electrical devices. With the scaling down of modern electronics both in size and power consumption, comes the idea of the internet of things which constitutes low power device modules interconnected and making decisions without human intervention. Some of these devices may be located in remote locations where it may not be possible for humans to reach. The need is to make these devices independent power producers so that they are self-operable and non-reliant on the electric grid.

One possible energy scavenging device is the triboelectric generator. It consists of atleast one insulator which on repeated rubbing with an appropriate material, determined by consulting the triboelectric series [1], can be made to consistently carry either positive or negative surface charge. The back of the insulator is coated with a conductor and fixed to the base. The conducting part is connected externally by conducting wire to a moving conducting plate as shown in Figure 1. Any motion of the plate will lead to charge flow through the wire from one conductor to the other due to electrostatic induction effect. Thus we can build a vibration system that can convert vibration energy to electrical energy and can be attached to any vibrating surface.

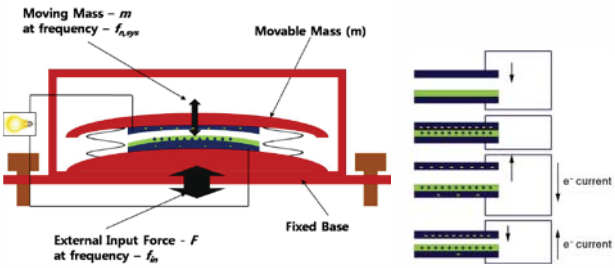

Figure 1. Simple vibration based TEG and the working mechanism of converting motion to electrical current flow.

Several vibration system designs have been demonstrated in the literature with respect to TEGs [2-5] and also using other technologies [6]. In this work we explore how to design a freely vibrating TEG excited indirectly by input forces. Two systems are designed and implemented and an impact based model is proposed for analysis. The model simulation is shown to be consistent with the experimental output. The design modification improves the output voltage as well as the working bandwidth of the TEG.

2 Methodology

2.1 System Model

The lumped model for the TEG impact based vibration system is shown in Figure 2.

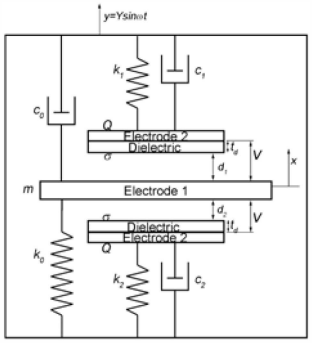

Figure 2. Lumped model for vibration type TEG.

For a contact-mode triboelectric generator, the output voltage between the two electrodes is given as,

$$V = -\frac{Q}{S\varepsilon_0}\left(\frac{t_d}{\varepsilon_r} + x(t)\right) + \frac{\sigma\, x(t)}{\varepsilon_0} \qquad (1).$$

where Q represents the amount of charges transferred between the two electrodes, S is the area of the electrodes, ε_0 is the permittivity of free space, ε_r is the insulator dielectric constant, t_d is the dielectric thickness and σ is the surface charge density on the dielectric [7].
From equation (1), the open-circuit voltage can be determined to be

$$V_{OC} = \frac{\sigma\, x(t)}{\varepsilon_0} \qquad (2).$$

Therefore, the output voltage is directly proportional to the movable mass displacement *x(t).* This displacement is modelled as a non-linear impacting vibration system. The set of equations of motion for three situations depending on the impacting condition are given as,

$$\begin{aligned} &x \geq d_1 \\ &m\ddot{x} + (c_0 + c_1)\dot{x} + (k_0 + k_1)x - k_1 d_1 = -m\ddot{y} \\ &-d_2 < x < d_1 \\ &m\ddot{x} + c_0\dot{x} + k_0 x = -m\ddot{y} \\ &x \leq -d_2 \\ &m\ddot{x} + (c_0 + c_2)\dot{x} + (k_0 + k_2)x - k_2 d_2 = -m\ddot{y} \end{aligned} \qquad (2).$$

where d_1 and d_2 are distances between the moving mass (m) and top and bottom dielectrics respectively, c_0, c_1 and c_2 are damping coefficients and k_0, k_1 and k_2 are spring stiffness as shown in Figure 2. The input force (y) is assumed to be sinusoidal in nature with input frequency ω and amplitude Y. [8]

2.2 Parametric Variables

Maximum amplitude vibration is expected to occur under resonance conditions that is when the natural frequency of the system is the same as the input frequency. In order to scavenge energy from the environment it is necessary to first measure the fundamental frequency and g-forces of the force input source. Most environmental mechanical vibration sources are characterized as low force and low frequency [9]. The natural frequency of the vibration system is given by $\omega_n = \sqrt{k_{eq}/m}$. The mass ($m$) is the product of material density and volume. Both the material and volume may be part of the design specifications. The overall spring stiffness (k_{eq}) is used to determine the required individual spring stiffness (k) by solving the force balance equations for the concerned structure. This is then used to design the spring based on its stiffness equation.

In this work we use a coil spring structure with stiffness equation,

$$k = \frac{Gd^4}{8nD^3} \qquad (3).$$

where G is the shear modulus for stainless steel, d is the wire diameter, n is the number of coils and D is the coil diameter. The length is related to the coil diameter as $L = \pi nD$ [10]. The dimensions must be selected such that the spring does not buckle or break.

2.3 Design Algorithm

The design methodology requires defining the objective and listing the constraints. Maximum vibration motion and contact is expected to occur under resonance, thus the objective is defined to be to achieve this condition. The constraints include material and dimensional specifications and the pre-measured input g-forces and frequencies. We can then analyze our system as described previously and determine the required individual spring stiffness and then design the spring accordingly. Thus the system design reduces to a spring design problem.
In this work, as illustrated in Figure 3, copper is used as the material for the moving mass with value *50grams.* A separation gap (d_1,d_2) of about *5mm* is required. Input forces of *0.4g* at *13Hz* are expected. Using the system natural frequency equation, the values for k_{eq} and individual k are calculated first for single-impact TEG and then for double-impact TEG design. For single-impact, spring *k=83N/m* and for double-impact design *k=41.5N/m.* This is because the double-impact TEG uses twice the number of springs as single-impact design. The final spring designs are shown in Figure 3. The spring dimensions are determined using a professional spring design calculator from reference [10].

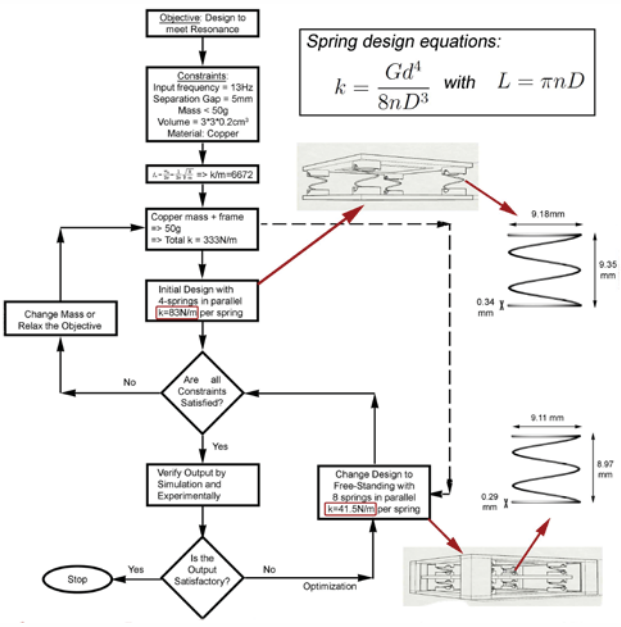

Figure 3. Design procedure for single-impact and double-impact TEG systems for optimal output along with the required spring dimensions for each proposed structure.

2.4 Device Fabrication

The materials used for the triboelectric devices are copper as electrodes and polydimethylsiloxane (PDMS) as the dielectric. PDMS lies at the negative end of the triboelectric series while copper lies at the positive end. Also copper is a high density metal, thus packing in greater mass in small volume. This allows us to reduce the size of the overall device. PDMS was synthesized from Sylgard 184A mixed in ratio 1:10 and then spin-coated and cured on the copper plate at 80°C for 4 hours after degassing. The construction of the single and double-impact TEG based on the proposed design is shown in Figures 4 and 5. In the case of double-impact generator, two TEG devices are coupled to get enhanced output. The initial gap between the plates is set at 5mm. This is done by considering the initial displacement of the springs $x_0 = mg / k_e$, before attaching the devices. For single-impact design, the calculated stiffness per spring is 80N/m and 4 springs are used, while for double-impact design the stiffness is 40N/m per spring and 8 springs are used. The final coil spring dimensions are shown in Figures 4 and 5.

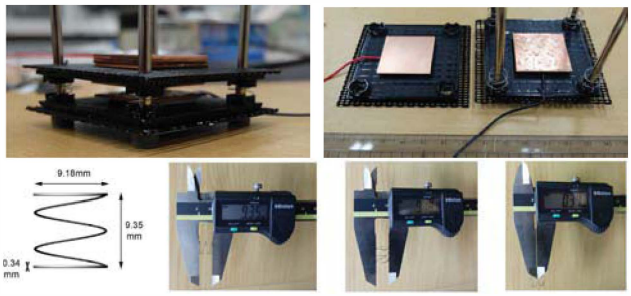

Figure 4. Single-impact TEG device fabrication. Bottom images show spring design.

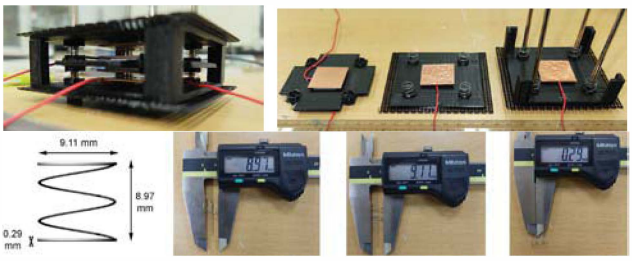

Figure 5. Double-impact TEG device fabrication. Bottom images show spring design.

2.5 Experimental Method

The vibration tester setup is shown in Figure 6. The devices were attached on top of a linear motor which is driven by an amplifier. It is secured to the table. The input frequency is controlled by a function generator. and varied from 1Hz to 50Hz. The input amplitude is kept constant and measured using an accelerometer. The voltage output was observed on a Tektronix oscilloscope. Since the oscilloscope measures voltage across an impedance, the measured voltage maybe considered as loaded voltage rather than open circuit voltage.

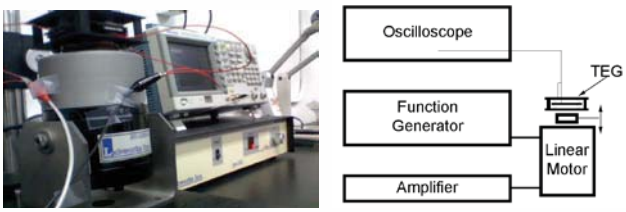

Figure 6. Vibration tester setup and block diagram.

3 Results

3.1 Single-Impact TEG Vibration Behavior

The single-impact TEG showed an output voltage of 3V peak-to-peak at 13Hz resonance frequency. The alternating peaks were singular (one waveform per impact). The voltage versus input frequency output showed a rise in voltage at 13Hz resonance frequency followed by a linear rise upto about 28Hz. Thus the bandwidth of operation for this device is 15Hz.

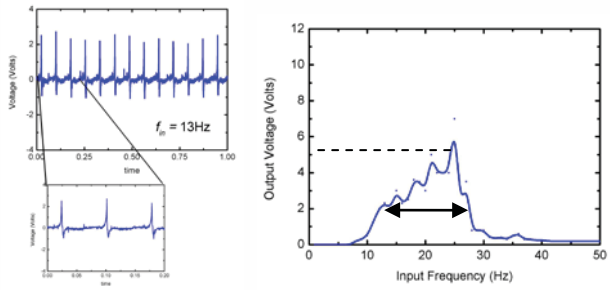

Figure 7. Left: Voltage output at input frequency 13Hz. Right: Voltage output versus input frequency for single-impact TEG design.

3.2 Double-Impact TEG Vibration Behavior

The double-impact TEG showed an output voltage of 12V peak-to-peak at 13Hz resonance frequency. Multiple peaks reflecting the damped vibration behavior of the moving mass was observed. An operable bandwidth of 13Hz to 48Hz, that is a span of 35Hz was observed.

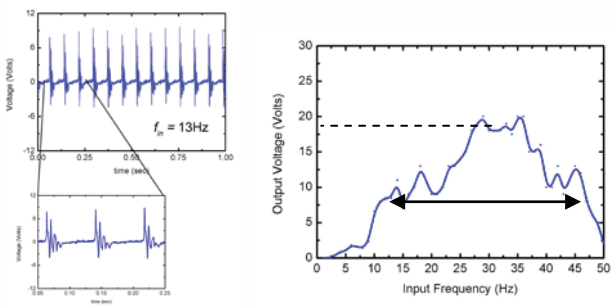

Figure 8. Left: Voltage output at input frequency 13Hz. Right: Voltage output versus input frequency for double-impact TEG design.

3.3 System Model Simulation

Based on the system model as described in Section 2.1 the vibration response was obtained for single-impact and double-impact TEG. From equation 1, the maximum output voltage is proportional to the vibration displacement. The displacement behavior with respect to time for the two designs is obtained by simulating the equations using MATLAB/Simulink. The Simulink model is based on equation 2. The input parameters used are given in Table 1 and the output response is shown in Figure 9. It can be seen from the output that the proposed model predicts the increase in operable bandwidth for the double-impact TEG system.

Table 1. .Parameter values for model simulation

	Single-Impact System	Double-Impact System
f_0	13Hz	13Hz
f_1	-	50Hz
f_2	100Hz	100Hz
ζ_o	0.002	0.002
ζ_1	-	0.02
ζ_2	0.5	0.5
d_1	-	2mm
d_2	4mm	4mm
$Force_{in}$	1g	1g

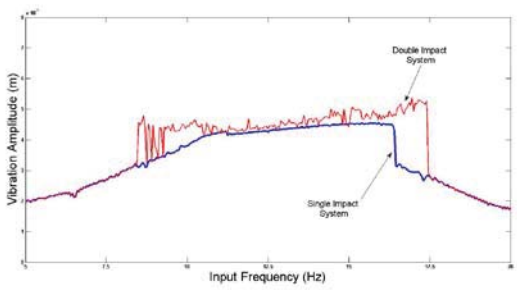

Figure 9. Simulation output shows increase in operable bandwidth for double impact system when compared to single impact system model.

4 Conclusion

In conclusion, vibration analysis and design methodology was demonstrated for single-impact and double-impact TEGs. A vibration model was proposed and verified experimentally and by simulation. A design algorithm was formulated based on the analysis for the construction of the two TEGs. The double-impact TEG showed four times increase in voltage output due to the coupling of two generators. It also showed an increase in operable bandwidth as predicted by the model simulation.

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